Effects of Low Levels of Carbon Monoxide on Vision of Smokers and Nonsmokers

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ABSTRACT

The scotopic sensitivity, reaction time, eye movements, and visually evoked cortical potentials of 12 nonsmokers and 6 smokers were measured during the course of 3 hr of exposure both to air and to 200 ppm CO in air. No significant degradation in performance was observed for any of these measures in either group during the course of the exposure.

IT IS STILL NOT CERTAIN what behavioral effects result from exposure to levels of carbon monoxide (CO) that are too low to produce subjective symptoms. It seems to be generally agreed that blood carboxyhemoglobin (HbCO) levels lower than 15% produce no symptoms.[1,2]

The measurement of perceptual processes has been a widely used method of studying these effects. Some regard vision as the most sensitive measure of a variety of toxicities,[3,4] including CO poisoning.[5,6] In many instances it is the first part of the body to show the effects of a harmful substance.[7]

McFarland and his coworkers were among the earlier investigators to report that visual processes are degraded by small amounts of CO.[8-10] Yet most of the findings, whether for visual or nonvisual processes, are in dispute. Two examples will suffice. McFarland found that levels of HbCO around 10% produced impairments in absolute (scotopic) threshold. But Weir et al.[11] found no significant changes in dark-adapted thresholds for identification of shapes at HbCO levels up to 20%; and Beard and Grandstaff[12] could not draw any conclusions with HbCO levels up to 7%.

Similarly, in investigating reaction time (RT), Stewart et al.[13] and Weir et al.[11] found no impairments at HbCO levels of 13%, whereas Ramsey[14] reported that RT was poorer at HbCO levels of 3%.

A second question of great interest concerns the differences between smokers and nonsmokers. Smokers are, of course, regularly exposed to CO and consequently have elevated HbCO levels compared to nonsmokers. The question arises whether exposure to additional amounts of CO produces more impairment in behavior than occurs for nonsmokers. Or does the long-term exposure to CO produce an adaptation that serves to protect them from harmful effects to which nonsmokers are susceptible?

A number of studies have shown that physiological adaptations occur with repeated or chronic exposure to CO,[15-18] but the effects of these changes on performance are not certain. Bartlett[19] and Lawther and Commins[20] argue that cigarette smoke and ambient CO are not additive, and that smokers may be less susceptible to low concentrations of CO than nonsmokers. On the other hand, von Post-Lingen[21] concluded that continued exposure to low levels had a cumulative effect on critical flicker fusion (CFF), thought to be a sensitive measure of neural functioning. Barlow and Baer[22] found some differences in CFF between heavy and light smokers, and the reports of a relationship between HbCO levels and traffic accidents[23,24] suggest that the effects on performance may be additive.

The purpose of this study was to obtain further data on the effects of low concentrations of CO on visual processes and to compare the effects on smokers and nonsmokers.

Materials and Methods

Subjects

Eighteen staff members of the Laboratory, both civilian and military, volunteered to take part in the experiment. Twelve reported that they had never smoked or had not smoked in the last 3 yr. Six were observed to be heavy smokers (at least 30 cigarettes per day). The average age of the nonsmokers was 27 yr (range, 19 to 39); that of the smokers was 34 yr (range 21 to 43). Only one smoker was younger than 30 yr, and only one nonsmoker was older than 30 yr.

Tests

The tests were selected on the basis of the results of preliminary experiments that appeared to show that these were the most promising.

Scotopic sensitivity. Scotopic sensitivity was measured with the night vision sensitivity test,[25] which presents to the dark-adapted subject 60 pairs of lights of different size and intensity at 12 positions in the visual field for an exposure duration of 1 sec. The results can be analyzed for

the number of correct stimuli reported, the size and intensity of the test lights seen, and the spatial distribution of errors.

Simple and choice reaction times. Reaction times were measured as follows. The subject monitored a 15-cm ground glass aperture about 50 cm from his eyes. The aperture could be illuminated with either red or blue light of equal brightness. The subject's task was to turn off the light as quickly as possible by pressing a button. Simple RT was the mean reaction time of 20 trials by the right hand in response to the blue light. When choice reaction time was being measured, either color could go on. The subject controlled two buttons and was obliged to respond with the right hand to turn off the blue light and with the left hand to turn off the red light. (Pressing both buttons at once would not work.) Mean choice reaction time was the average of 20 trials, ten with each hand, in random order.

Eye movements. Eye movements during reading tasks were recorded with a Biometrics eye-movement monitor, model SGHV-2. There were two reading tasks. In the first, the subject searched through ten lines of typewritten "p's" looking for randomly interspersed "q's." A series of such pages was typed containing 16 to 18 of the target letters. In the second task the subject read a short typewritten paragraph from a selection of paragraphs taken from Nordsiek's article, "The Sweet Tooth."[26] After some editing, they were of uniform length and difficulty and could be presented in any order and still maintain some continuity. Both the letters and paragraphs were presented in counterbalanced order. The same page of letters of the same paragraph was never used twice for a given subject. The letter-search results were analyzed for number of target letters found, and both tests were analyzed for total time to read the material, number of fixations, and number of reversals.

Visually evoked cortical responses. A 10° blank field of white and a checkerboard (alternating black and white squares of .63°) elicited visually evoked cortical responses (VERs). They were illuminated by a Grass PS-2 photostimulator flashing two or eight times per sec. Bipolar electrodes were located 2 and 7 cm above the inion on the midline of the scalp; a ground was on the ear. The signals were amplified by a Grass P511 preamplifier and summed by a Technical Measurement Corporation computer of average transients (CAT 400C). One hundred 1-sec intervals of cortical activity immediately following the onset of the stimulus were analyzed by the computer. The order of the targets and of the flash rates was random from one session to another.

Administration of Gas

The subjects breathed through oral nasal masks that were attached to wall outlets so concealed that the subjects could not see the outlet to which the mask was attached. Subjects breathed either pure compressed air or air plus 195 ppm CO for 18 min; they completed the final VER without the mask. The HbCO level in the blood was measured immediately after testing with an Instrumentation Lab Inc. CO-oximeter, model 182. The mean HbCO level of the nonsmokers after exposure to the CO was 9%, which agrees reasonably well with the nomogram of Stewart et al.[13] The HbCO levels of the smokers after exposure to the CO was higher than that of the nonsmokers and ranged from 10.2% to 13.3%. The HbCO levels of the smokers at the end of the control session ranged from 3.1% to 7.2%. This represents a decrease from their usual levels measured several weeks after the experiment of 6.7% to 9.0% and is presumably due to the reduced smoking during the experiment. The latter values also agree well with previous reports of the HbCO levels of rather heavy smokers.[27,28]

Experimental Design

Prior to the experiment, each subject practiced for several days on the reaction-time apparatus and on the night vision test until his performance reached a plateau. Then he was subjected to the battery of tests to familiarize him with the procedure.

Each subject was then tested twice, once while breathing pure air and once while exposed to CO. Half the subjects in each group breathed the CO first; half breathed air first. The subjects were not informed as to which session involved exposure to CO.

During each session there were three consecutive test runs, separated by 5-min rest periods during which the subjects could take a drink or smoke a cigarette if they wished. It is common to forbid subjects who are smokers to smoke during the course of such an experiment. It is, however, also common for smokers to become distressed under such enforced abstinence. It is then difficult to say if changes in performance are the result of the experimental conditions or of the subject's emotional state. We thought it preferable to permit smoking during the rest periods.

The test runs began 30, 75, and 165 min after the start of the session. The tests were always given in the same order: night vision test, reaction time, eye movements, and the VERs. All the nonsmokers were tested first.

Results

Exposure to Three Hours of Carbon Monoxide

Night vision. The mean number of correct responses on the night vision test (corrected for guessing) are shown in Figure 1. There was no decline in sensitivity for either group as a result of exposure to CO. The scores for the nonsmokers were virtually identical during the course of exposure to both air and CO. Every smoker, however, improved during the control condition; this improvement was significant ($\chi_r^2 = 8.35, P < .02$) according to the Friedman analysis of variance by ranks.[29]

Reaction time. There were no significant changes for either the simple or the choice reaction time for either group under either condition (Table 1). The progressive reduction in mean simple RT for the smokers in air and their increase in choice RT under CO did not approach significance.

Eye movements. Table 2 gives the results of the tests for eye movements.

Table 1.—Mean Simple and Choice Reaction Times

Condition	Simple Reaction Time in msec			Choice Reaction Time in msec		
	Hour 1	Hour 2	Hour 3	Hour 1	Hour 2	Hour 3
Nonsmokers						
Air	199	197	194	304	315	301
CO	215	202	202	316	308	315
Smokers						
Air	257	253	238	447	443	458
CO	268	269	270	423	450	457

Consider first the results of the nonsmokers in the letter search. There were no significant changes in the time taken to do the letter search under air or CO. In the air control, however, the number of fixations and reversals increased with successive tests. The increase in reversals was significant ($\chi_r^2 = 4.66, P < .02$), but the increase in

Table 2.—Eye Movements During Letter Search and Reading

Task	Air Exposure			CO Exposure		
	Hour 1	Hour 2	Hour 3	Hour 1	Hour 2	Hour 3
Nonsmokers						
Letter search						
Time to count in sec	32.3	29.3	32.6	30.6	30.8	28.3
Fixations, no.	118.2	123.7	131.3	120.2	121.2	117.5
Reversal of fixations, no.	26.7	29.6	40.7	29.2	27.4	30.8
Mean error in count	1.0	1.9	0.5	1.7	0.9	0.6
Reading						
Time to read paragraphs, in sec	12.0	11.3	11.6	11.9	11.6	10.7
Fixations, no.	46.8	47.6	49.5	48.5	47.2	43.8
Reversal of fixations, no.	7.3	9.3	9.3	8.1	7.0	5.9
Smokers						
Letter search						
Time to count target letters, in sec	46.6	41.6	44.7	37.5	38.2	32.2
Fixations, no.	151.0	134.5	135.0	126.5	119.2	96.5
Reversal of fixations, no.	18.8	16.8	15.2	21.5	15.5	12.8
Mean error in count	0.6	1.8	0.6	1.0	1.2	0.4
Reading						
Time to read paragraphs, in sec	17.6	16.9	18.1	16.7	17.5	17.2
Fixations, no.	63.5	62.0	70.0	71.0	54.5	63.8
Reversal of fixations, no.	12.5	10.5	11.5	9.5	7.5	11.5

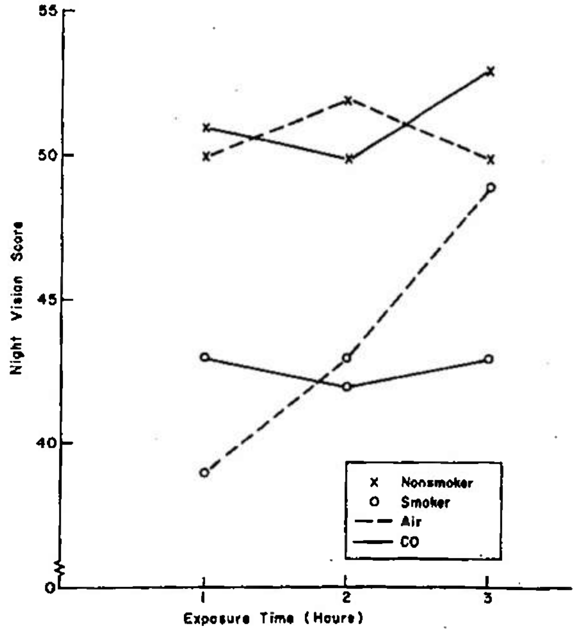

Fig. 1. Mean night vision scores on the three tests during the air and CO sessions for nonsmokers and smokers.

fixations was not. Under both conditions the number of errors declined at the end of the session, but in neither case did the change approach significance. When reading the paragraphs, none of the changes was significant.

None of the changes for the smokers was significant. All the mean scores for the letter search improved under both CO and air, suggesting a practice effect, rather than an experimental effect.

Visually evoked cortical response. Figure 2 shows typical visually evoked cortical responses to targets illuminated

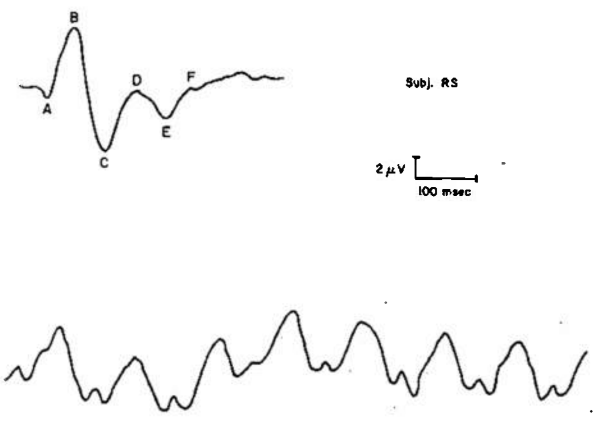

Fig. 2. Examples of visual evoked responses to the slow rate and to the fast rate. The letters on the curve for the slow flash rate indicate the main components of the electrical response of the brain to the stimulus used in this experiment.

2 and 8 times per sec. These VERs are different for every subject but are constant for a given subject under the same conditions. The VER to the slow flash rate has several major components, of which the BC component, the most prominent for every subject, was chosen for analysis. This portion of the VER has been shown to be sensitive to such stresses as hyperbaric pressure,[30] and it is in this part of the evoked response that Hosko[31] found changes resulting from CO exposure. The mean amplitude and standard deviation of the eight large peaks were calculated for the fast flash rate. The results are presented in Table 3.

Among the nonsmokers, there were no significant changes in either the mean amplitude of the major component of the slow flash rate or in the mean amplitude of the responses to the fast flash rate.

The changes for the smokers are, in general, small. There is an appreciable increase in amplitude only for the response to the blank field at 8 flashes per sec in the air exposure, but it falls short of significance.

Comparison of Performance under Air and Carbon Monoxide

Since there were almost no changes in performance during the course of a given session under exposure to air or CO, we combined the results of the three tests in each session and compared the performance of each group of subjects in the two conditions. The two sets of results are similar.

Night vision scores and reaction times were both poorer in CO, but these differences were not significant.

In the eye movement results, the smokers took less time to search the letters and made fewer fixations under CO, but this is the result of large, progressive improvement in the scores of two of the subjects who were exposed to CO during their second sessions. Practice on this test was limited to the single familiarization session, in contrast to the extended practice given on the night vision and reaction-time tests. The mean improvement is, therefore, probably a practice effect, and we attach no importance to it.

The mean amplitudes of the VERs are generally lower in CO than in air for all stimuli on each of the three runs per session for both groups. Analysis of variance shows, however, that for the nonsmokers none of these changes is significant. For the smokers, only the changes for the checkered target at 2 flashes per sec were significant ($F = 10.77, P < .01$). But none of the individual means is significantly different from its pair.

Discussion

There is virtually no evidence in these results that breathing 195 ppm CO in air for 3 hr, enough to raise the HbCO level in blood by about 10%, has any effect on the visual processes tested. This is surprising in view of the fact that the tests were selected on the basis of extreme sensitivity for the presumed effects. For example, many studies show that hypoxia exerts a greater effect on peripheral than on foveal visual stimuli;[32] furthermore, the decrements are greatest at threshold levels of luminance

Table 3.—Mean Amplitude* of Visual Evoked Responses to Blank and Checkered Field Illuminated Two and Eight Times a Second

Task	Times per sec	Air Exposure Hour 1	Air Exposure Hour 2	Air Exposure Hour 3	CO Exposure Hour 1	CO Exposure Hour 2	CO Exposure Hour 3
Nonsmokers							
Blank	2	7.60	8.14	7.29	7.28	6.21	7.36
Check	2	11.06	10.40	11.28	8.35	9.12	9.01
Blank	8	7.43	8.42	7.96	5.38	6.59	6.80
Check	8	6.79	6.76	7.38	5.62	5.62	5.49
Smokers							
Blank	2	7.48	7.84	7.40	6.14	8.56	8.00
Check	2	11.93	13.20	13.56	8.60	11.04	10.60
Blank	8	7.24	7.90	11.46	6.88	8.18	7.82
Check	8	5.66	5.86	6.32	4.02	5.96	5.36

*Amplitude in μV.

and decrease at higher luminances.[33,34] Since a major consequence of breathing CO is hypoxia, we would expect the night vision test, with its perimetric aspect, to be a particularly sensitive measure of the loss of oxygen.

Our results, however, conform to a growing body of evidence that low levels of hypoxia or CO do not produce any significant behavioral changes. Although McFarland has consistently reported decrements with low concentrations of CO, he has nevertheless long maintained that highway levels of CO do not impair scotopic sensitivity,[2] and he has recently reported that HbCO levels as high as 17% do not seriously affect driving performance, as reflected by such tests as, among others, dark adaptation.[35]

The discrepancies in the various findings can result from many different factors. Consider the reaction time studies: Denison et al.[36] concluded that only unpracticed subjects suffer a degradation of RT upon exposure to low levels of CO. In view of the rapid improvement in RT that often occurs during the first few trials, it would seem that RT studies with unpracticed subjects would be very difficult to interpret. Ledwith[37] showed that RT responses could be broken down into pure RT and movement time and only the movement time suffered under hypoxic conditions; RT was unaffected. Kobrick[32,38] has found relatively little degradation in RT to central stimuli. Finally, in Ramsey's study[14] HbCO levels were raised by exposure to automobile exhausts; other pollutants may have been responsible for the significant reduction in RT that his subjects showed. Our subjects were well practiced, viewed the stimuli foveally, made no large movements, and breathed no extraneous pollutants.

It is generally agreed that VERs are unaffected by HbCO levels lower than about 15%.[13,31,39]

In summary, we concur with the conclusions of Stewart[40] that "decrements in cognitive task performance observed in subjects with HbCO saturations of less than 5% have not been proved and are definitely suspect." We also suspect that the same is true for most basic sensory and perceptual processes for higher HbCO levels as well. Wright et al.[41] have argued that the low levels of CO do not degrade the performance of any given individual to a significant extent, but that the performance of a group of subjects will be significantly worse. In other words, most subjects will show only a very slight degradation, but a degradation nonetheless. Wright and associates tested 50 subjects in their study. We have tested less than half that number in this study, but we have not found much evidence of trends that might reach statistical significance with larger samples.

As for the question of whether smoking renders an individual more or less susceptible to the effects of additional small increases in CO concentrations, there is virtually no indication in these results that smokers were more adversely affected than nonsmokers by the experimental exposures. On the other hand, there was an apparent improvement in the mean scores of the smokers on two of the tests during the air control, when, of course, they were not smoking at their usual rate. Moreover, the performance of the smokers appeared to be worse than that of the nonsmokers in several instances. It is not possible to state the cause of the difference, however, because of the small size of the samples and because the smokers were older than the nonsmokers. We have found in another study,[42] however, that smokers appeared to be more affected by CO than nonsmokers, when tested using the phenomenon of visual masking.

It would be of great interest to examine large, matched groups of smokers and nonsmokers. It should be noted that the mean HbCO level of smokers increased from about 8% to 12% after the experimental exposure, an increase of only 4%. In contrast, the HbCO level of the nonsmokers was 9%, compared to their assumed typical level of less than 2%, an increase of 7%. Vogel et al.[43] also found that

"nonsmokers . . . had a greater increment in HbCO (20.1 vs 18.5) "after both were exposed to 225 ppm CO in air for the same period of time. Do these findings indicate that smokers are handling CO differently than the nonsmokers, perhaps as a result of having undergone some sort of adaptation?

If the increase in HbCO with continued exposure is a negatively accelerating rather than a linear function, or if after 3 hr of exposure to 200 ppm CO the HbCO curve is approaching the saturation plateau, then we would conclude that the smaller increase in HbCO concentration for the smokers is merely an artifact of their having started at a higher point on the curve and having reached saturation levels sooner than the nonsmokers. The saturation level for exposure to 200 ppm CO is around 25% HbCO, however, and after 3 hr of exposure to that concentration the curve clearly is not close to saturation.[13] Moreover, the results of Stewart et al.[13] show that the absorption curve is only slightly negatively accelerating, and indeed the theoretical treatments of HbCO formation[44,45] predict linear functions within the range of exposure encompassed by this experiment. These considerations suggest, then, that smokers may indeed be handling CO differently than the nonsmokers. And they call attention to the question of the effects of long-term exposure to CO, a question that appears to be of more interest than the effects of short, acute exposure.

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

carbon monoxide; scotopic sensitivity; perimetry; environmental stress; sivual evoked responses; eye-movements; reaction time

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The scotopic sensitivity, reaction-time, eye-movements, and visually evoked cortical potentials of 12 nonsmokers and six smokers were measured during the course of three hours exposure both to air and to 200 ppm CO in air. The field of view of the smokers was also measured. No significant degradation in performance was observed for any of these measures in either group during the course of the exposure. The smokers appeared to be worse

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than the nonsmokers on several tests.